THE EFFECTIVE CROSS SECTION FOR THE PRODUCTION OF THE $C^3\Pi_u$ STATE OF N_2 WHEN BOMBARDED BY LOW ENERGY ELECTRONS

James Louis Poole

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

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by

James Louis Poole

Thesis Advisor: Edmund A. Milne

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James Louis Poole
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1964

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
December 1972

ABSTRACT

This paper describes a system and its calibration for measuring the effective cross section for the production of the $C^3\Pi_u$ state of N_2 in the lowest vibrational level under bombardment by electrons in the 150 eV to 1.2 KeV energy range and the measurements which were made.

With a gas pressure of about 3×10^{-2} torr, the effective cross section of the second positive system of N_2 under bombardment by 150 eV electrons was found to be $(1.42 \pm .38) \times 10^{-17}$ cm^2. This value is believed to be very near the peak value of the cross section.

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I. INTRODUCTION

A knowledge of the properties of upper atmospheric gases is required to understand phenomena occurring in the upper atmosphere such as airglow, aurora, and gas discharge processes. The objective of this research was to measure the effective cross section of one of the most important of these gases, molecular nitrogen, in forming the $C^3\Pi_u$ state of N_2 under bombardment by low energy electrons in the 150 eV to 1.2 KeV range. This project was undertaken in support of research funded by the Naval Ordnance Laboratory. References 1, 2 and 3 reported work done previously in the design and calibration of the experimental apparatus, and this paper describes modifications to the optical and electron gun systems, and the recalibration results of the detection system, in addition to those discussed in Ref. 3. Finally, measurements of the effective cross section of the $C^3\Pi_u$ state of N_2 are reported along with the difficulties encountered.

II. THE CROSS SECTION EQUATION

The purpose of the experiment was to measure the effective cross section of the $C^3\Pi_u$ state of N_2. In order to do this, the cross section must be defined in terms of measurable quantities, as outlined below.

The lowest vibrational level of the $C^3\Pi_u$ state of N_2 decays electromagnetically to the $B^3\Pi_g$ state of N_2 in the v" progression (0,0), (0,1), (0,2), (0,3), (0,4) and (0,5). The transition probabilities per unit time for these transitions are well known and are presented later. The wave length for the transition of highest probability, the (0,0) transition, is 337.13 nm.

The rate equation for the total population of an excited state, N_k^*, is given by:

$$(1) \quad \frac{dN_k^*}{dk} = R_k - \sum_{f=0}^{n} \lambda_{of} N_k^* - Q$$

where R_k is the rate of formation of the excited state, λ_{of} is the probability per second of decay to the final state, f, and Q is the collisional de-excitation rate. If the gas is bombarded by electrons for a time greater than the mean life of the excited state, then the total population of the excited state is constant, and the excitation rate is equal to the de-excitation rates (i.e. steady state condition). If the gas pressure is sufficiently low then Q, the collisional de-excitation rate, can be ignored when compared to the other terms, as shown by Fontana [Ref. 2]. Then:

$$(2) \quad R_k = \sum_{f=0}^{n} \lambda_{of} N_k^* = \lambda_{oo} \sum_{f=0}^{n} \frac{\lambda_{of}}{\lambda_{oo}} N_k^*$$

The excitation rate R_k can be defined by the equation:

$$(3) \quad R_k \equiv \frac{n_G J V \sigma}{e}$$

from which the effective cross section, σ , can be obtained:

$$(4) \quad \sigma = \frac{R_k e}{n_G J V}$$

where n_G is the number density of molecules in the ground state within the volume V, J is the current density of the bombarding electrons (i.e. the electron beam), e is the fundamental unit of electric charge, and R_k is the rate of formation defined above. If the volume V is the interaction volume discussed later in this paper, defined to be a right circular cylinder of length L and a cross-sectional area A equal to the cross-sectional area of the electron beam, and J = I/A, then:

$$(5) \quad \sigma = \frac{R_k e}{n_G I L}$$

Reference 2 shows that at room temperature, n_G/n, the ratio of molecule density of molecules in the ground state to the total molecule density is 0.9999-----; therefore, to a very good approximation, n may be substituted into equation (5) above for n_G . Substituting equation (2) into equation (5) gives:

$$(6) \quad \sigma = \frac{e}{nIL} \lambda_{oo} N_k^* \sum_{f=0}^{n} \frac{\lambda_{of}}{\lambda_{oo}}$$

A detection system designed to count the number of (0,0) transitions would give a count rate, C:

$$(7) \quad C = \frac{d\Omega}{4\pi} \epsilon \lambda_{oo} N_k^*$$

where $d\Omega$ is the solid angle subtended by the detection system, ϵ is the efficiency of the detection system, and $\lambda_{oo} N_k^*$ is the transition

rate of the (0,0) transitions from the excited state K. If the gas is considered to be a pure ideal gas:

$$(8) \qquad n = \frac{P}{kT}$$

where P is the absolute pressure of the gas, k is the Boltzman constant, and T is the absolute temperature of the gas. Substituting equations (7) and (8) into equation (6) then gives the cross section equation:

$$(9) \qquad \sigma = \frac{4\pi k e}{d\Omega \epsilon L} \sum_{f=0}^{n} \frac{\lambda_{of}}{\lambda_{oo}} \frac{TC}{IP}$$

where $d\Omega$, ϵ and L, once determined, are constants of the experiment; T, C, I and P are the variables, and the transition probabilities per second, λ_{of} , listed below, are given by Nicholls /Ref. 4/.

$$\lambda_{oo} = 1.11 \times 10^{7} \text{ sec}^{-1}$$
$$\lambda_{o1} = 7.27 \times 10^{6} \text{ sec}^{-1}$$
$$\lambda_{o2} = 2.83 \times 10^{6} \text{ sec}^{-1}$$
$$\lambda_{o3} = 9.33 \times 10^{5} \text{ sec}^{-1}$$
$$\lambda_{o4} = 2.54 \times 10^{5} \text{ sec}^{-1}$$
$$\lambda_{o5} = 5.11 \times 10^{4} \text{ sec}^{-1}$$

III. EXPERIMENTAL APPARATUS

The experimental apparatus consists of six major subsystems, each of which is described below. They are: (1) the outer chamber, (2) the interaction chamber, (3) the vacuum system, (4) the electron gun system, (5) the optical system, and (6) the detection and counting system. Figure 1 is a schematic drawing showing the interrelationship of these subsystems.

A. OUTER CHAMBER

The outer chamber is a large aluminum enclosure, housing the interaction volume and electron gun, and connected to the vacuum system. All electrical connections to the interaction chamber, electron gun, and ion gauges pass through glass feed-throughs or coaxial connectors in the chamber walls. Inlets are provided for the connections between the interaction volume and pressure gauge and gas injection line. A vacuum is maintained by the vacuum system described below, and pressure in the outer chamber is measured with an ion gauge.

B. INTERACTION CHAMBER

The interaction chamber, hereafter referred to as the IAC, is that part of the apparatus where collisions between the electron beam and nitrogen molecules take place, and can properly be called the heart of the entire system. As shown in figure 2, it actually consisted of two concentric chambers with the inner chamber electrically insulated from the outer chamber. The ends of both chambers nearest to the electron gun were capped by a grounded flat circular face place with 1/8 inch diameter hole in the center to admit the electron beam. The ends opposite

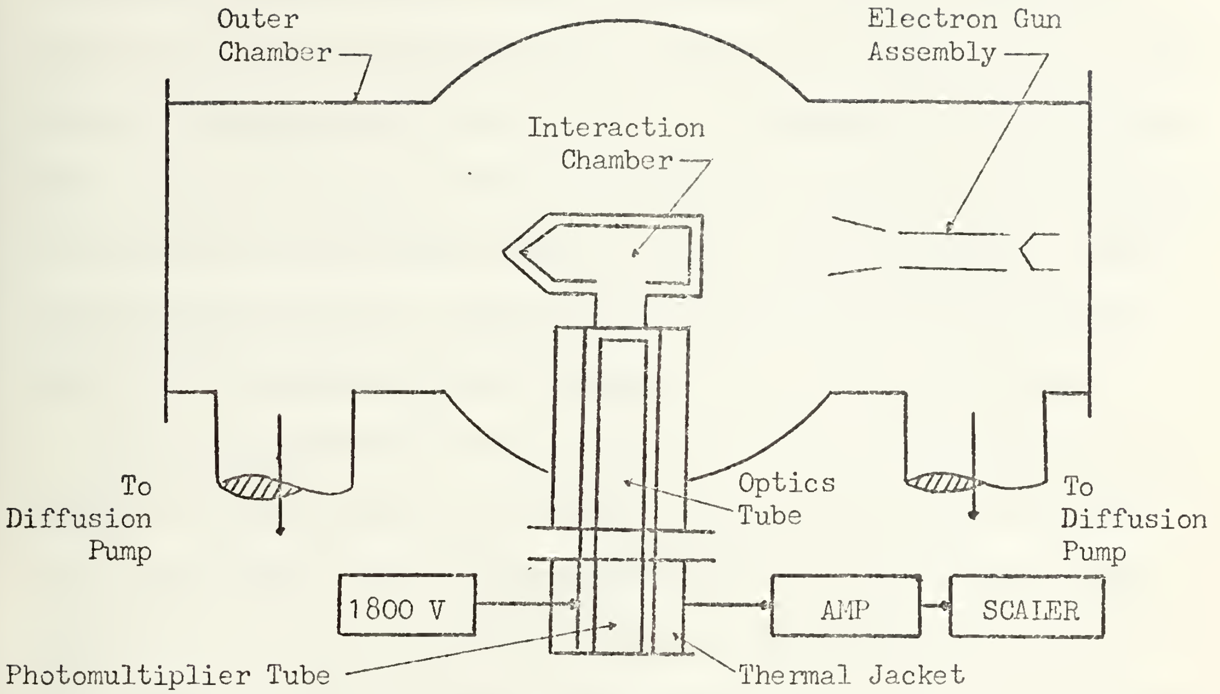

Figure 1. Experimental Apparatus

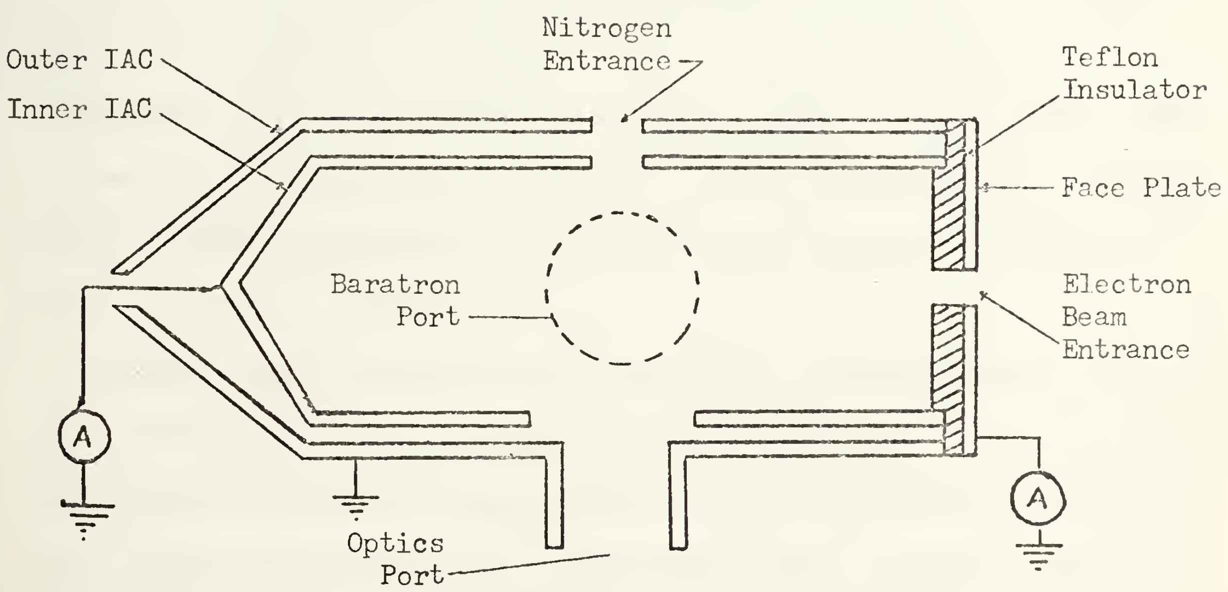

Figure 2. Interaction Chamber

the electron gun had center holes to facilitate optical alignment of the electron gun. In use, the inner chamber was closed so it was essentially a Faraday cup for the collection and measurement of the electron beam. The outer chamber served as an electrical shield to prevent stray electrons from contributing to the current to the Faraday cup. The result was that only those electrons which entered the hole in the face plate into the smaller chamber were measured as part of the beam.

Since the purpose of the experiment was to count only those photons emitted in the excitation of the gas, care was taken to minimize any light from outside sources, primarily the electron gun filament, from entering the optics. For this purpose, the inner chamber was covered with aquadag, a non-reflecting coating with good vacuum characteristics, and the optics were mounted at right angles to the electron beam axis.

The face plate mentioned above was grounded through a pico ammeter. This ammeter served a dual purpose: it served as an aid to the rough alignment of the electron gun, and it gave a measure of the gross output of the gun. The pico ammeter connected to the other end of the IAC provided a direct measurement of the electron beam current I, required in the cross section equation.

Nitrogen gas was admitted into the IAC by a precisely controlled leak valve and was maintained at a constant pressure by the pressure differential established between the IAC and outer chamber. This pressure could be measured by three independent means: a thermocouple, an ion gauge, and a Baratron barometer. The Baratron is a very precise measuring instrument for the pressures required in the IAC and is capable of recording differences as small as 10^{-5} torr. It was connected with its high pressure side to the IAC and its low pressure side to a reference

vacuum of about 10^{-7} torr. With a pressure of 10^{-4} torr or higher in the IAC, the Baratron measured what was essentially the absolute pressure P, required in the cross section equation. The ion gauge was used as a check for the Baratron, but due to the relatively high pressures (for an ion gauge), its susceptibility to contamination by the nitrogen gas, and the fact that it acted as another light source, it was not used for measurements when readings were being made.

C. VACUUM SYSTEM

The vacuum system consisted of two six inch oil diffusion pumps rated at 1800 liters per second each, discharging to a single 15 cfm, two-stage mechanical pump. The cold trap of each diffusion pump was cooled with liquid nitrogen. Each diffusion pump operating along was capable of maintaining pressures less than 10^{-6} torr when gaseous nitrogen was not being admitted to the system, but when nitrogen was introduced to the IAC both pumps had to be used to maintain the proper pressure for the experiment. The electron gun was mounted directly above the intake of one of these pumps to prevent the gas streaming through the face plate hole from diffusing the electron beam any more than was necessary.

D. ELECTRON GUN SYSTEM

The heart of the electron gun system was the electron gun itself, a modified commercial television picture tube (RCA 7 JP-4) gun. The modifications included the grounding of lenses 2, 3, 4, 5 and the end deflection plates, as well as replacing the indirectly heated cathode with a directly heated V-shaped cathode made of 0.010- inch diameter tungsten wire. When the cathode was removed, the electron gun could be optically aligned with the IAC using a small HeNe laser.

The cathode was heated with a small ac voltage and maintained at a negative bias. The IAC was maintained at ground potential, as discussed above, so the electrons were accelerated toward the face plate hole with an energy equal to the acceleration potential (negative bias) in electron volts. A small dc voltage could be applied to the deflection plates to compensate for any small misalignment of the beam. The electron gun assembly is shown schematically in figure 3.

E. OPTICAL SYSTEM

The optical system was designed to collect photons emitted from the interaction volume at right angles from the electron beam and focus them on the face of the photomultiplier tube. It consisted of two positive lenses, an interchangeable narrow band filter, an aperture and field stop, all mounted in a brass tube to make a system of unit magnification. The optical system was isolated from the IAC by a quartz window, in order that the optical system could be removed as an integral unit for calibration without destroying the vacuum in the system.

The first lens was mounted with its focal point set at the center of the electron beam, passing parallel light through the filter to the second lens, which was set with its focal point on the face of the photomultiplier tube. Immediately in front of the first lens was a circular aperture of 22.22 mm diameter. The filter, with a nominal transmission wavelength of 340 nm, was tilted with respect to the direction of the incident light to bring its peak transmission closer to the 337.13 nm wavelength to be measured. The light was focused on a 22.22 mm by 3.175 mm slit in contact with the photomultiplier tube face. This slit was oriented with its long axis at right angles to the axis of the electron beam.

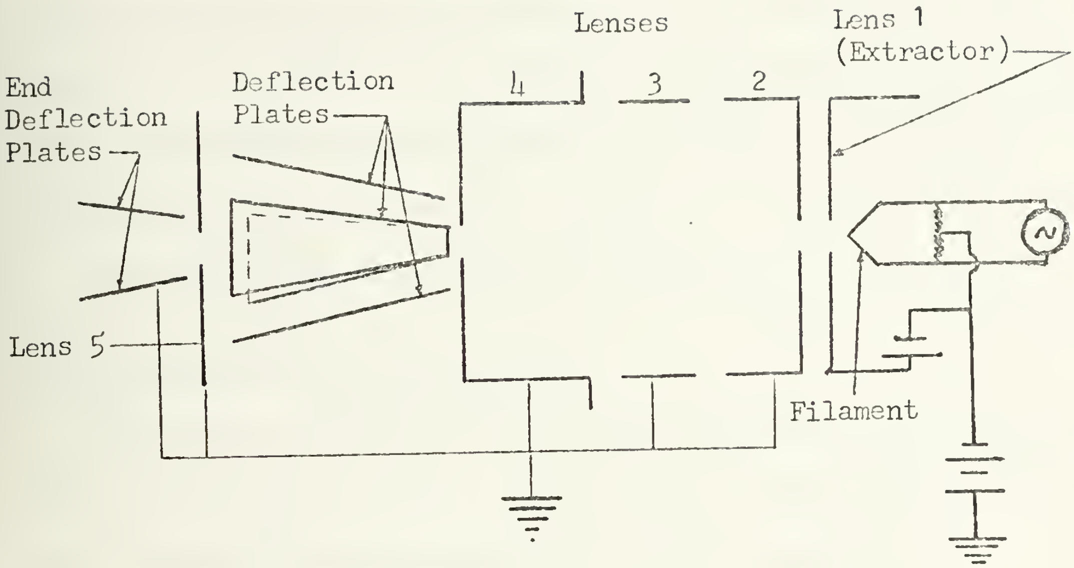

Figure 3. Electron Gun System

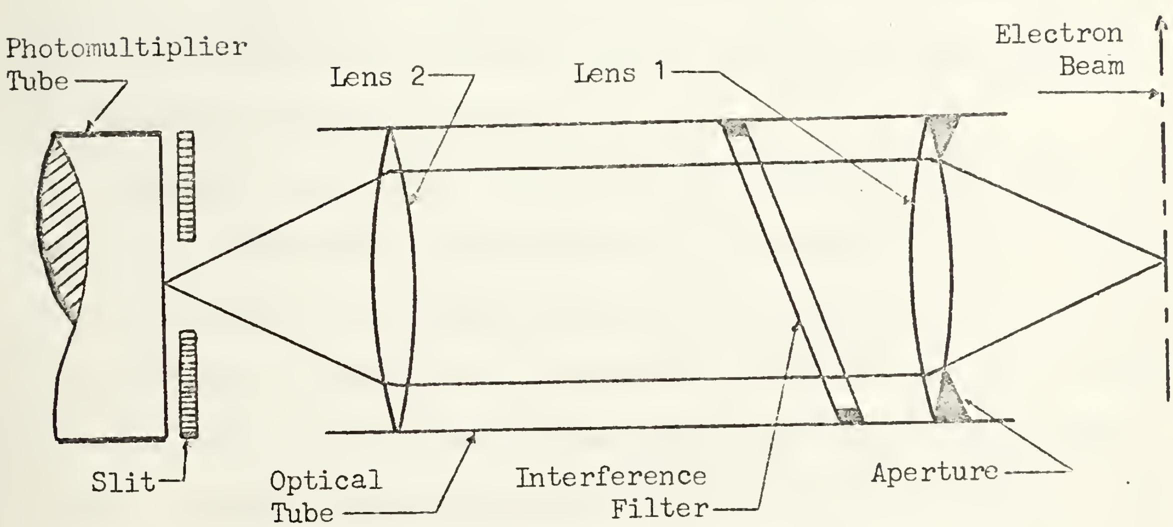

Figure 4. Optical System

The electron beam cross section and the 3.175 mm width of the slit then defined the interaction volume, with L in the cross section equation now fixed at 3.175 mm. The aperture diameter and the focal length of the first lens defined the solid angle of the optical and detection system required for the cross section equation.

The optical system is shown in figure 4.

F. DETECTION AND COUNTING SYSTEM

The photons collected by the optical system were focused on an RCA 6810A photomultiplier tube. The tube was cooled by liquid nitrogen boil-off to reduce its dark current to the lowest possible level. The liquid nitrogen boil-off was passed through a liquid nitrogen controller which served two purposes: it ensured that no liquid nitrogen passed through to the tube's insulating jacket (to prevent destruction of its linearity and stability by the extreme cold), and it regulated the temperature around the jacket with the aid of a thermistor. The temperature of the tube was measured with the aid of another thermistor located between the tube and its thermal jacket.

Although Norton /Ref. 3/ had reported no difficulty with fogging on the face of the photomultiplier tube or the second lens due to the cooling of the jacket, a defogging chamber was nevertheless provided between the tube and the second lens. A portable vacuum pump was used to evacuate the chamber and the chamber was then sealed with a small vacuum valve. A vacuum gauge was provided to ensure that the vacuum was held for the duration of measurements. This worked so well that after the defogging chamber was evacuated, there was no noticeable change in the vacuum for several days.

The electrical signal from the photomultiplier tube was then passed through an amplifier to a scaler-timer with a built-in pulse-height analyzer. It was found that the greatest signal-to-noise ratio was obtained by setting E_{min} at zero volts and E_{max} in the integral position, thus counting all pulses that entered the scaler-timer. As will be discussed later, this was a choice dictated also by the small number of counts caused by the low efficiency of the optical and detection systems.

IV. ALIGNMENT AND CALIBRATION

Alignment required the guiding of the electron beam into the interaction chamber and placement of the optical elements so that the photons emitted in the interaction volume were detected. Calibration required that a combined efficency of the optical and detections systems be obtained so that for a number of counts given by the scaler-timer, the actual number of emissions from the interaction volume was known.

A. ELECTRON BEAM

Optical alignment of the electron gun was accomplished using a small HeNe laser directed through the lenses of the gun and the holes in the IAC mentioned above. The filament was aligned by adjusting the point of the V to be in line with the center of the extractor lens (lens 1) of the gun, and herein is believed to be one of the problems encountered in focusing the beam for measurements. When the filament was heated to a temperature sufficient to extract electrons, it appeared to shift position enough to misalign the beam. Since the filament could be aligned only when it was cold, with the system open to atmospheric pressure, there was no way to correct for the misalignment of the heated filament. As a result of this problem, the beam apparently suffered severe diffusion effects along the vertical axis, as evidenced by a very poor response to corrections with the vertical deflection plates while having very good response to corrections with the horizontal deflection plates. As a result, beam current measurements in the IAC were reduced by factors of ten to a hundred from the current expected.

B. OPTICAL AND DETECTION SYSTEM

As discussed above, the lenses in the optical system were set at distances equal to their focal lengths from the center of the interaction volume and the photomultiplier tube, respectively. The focal length of each lens was determined on an optical bench with visible light and then corrected for the 337.13 nm wavelength they were to measure. The final focal lengths were determined to be 13.06 cm.

The optics tube and photomultiplier tube were removed from the apparatus and mounted opposite a calibrated lamp source. A spacer tube, with a slit at one end identical to the one at the face of the photomultiplier tube, was then positioned at the end of the optics tube with the slit located at the focal length of the first lens and oriented at right angles to the slit at the face of the photomultiplier tube. This arrangement duplicated the geometry of the optical and detection system when mounted on the experimental apparatus. With a known energy flux from the calibrated light, the efficiency of the optical and detection system could then be determined.

The lamp's intensity was so high at the standardized distance of 50 cm from the lamp it completely saturated the photomultiplier tube. Two methods were used to reduce the intensity to a tolerable level: the entrance slit was positioned two meters from the source, reducing the intensity to 1/16 of the intensity at 50 cm; neutral density filters were placed directly in front of the entrance slit. The actual transmission factors of the filters were obtained with the use of a spectrophotometer. Combining the energy flux data supplied with the lamp, the geometry of the optics system, and the transmission of the two neutral density filters with the narrow band filter installed in the optics

tube, it was possible to convert the energy flux of the lamp to photons per second entering the photomultiplier tube. From this and the counts per second given by the detection system, an efficiency of the optical and detection system was obtained:

$$\epsilon = (0.22915 \pm 0.0115)\ \%$$

V. EXPERIMENTAL PROCEDURES

When the cross section equation was developed, it was stated that the collisional de-excitation rate could be considered negligible if the gas pressure was sufficiently low. This pressure was previously determined to be less than 10^{-4} torr [Refs. 1, 2 and 3]. However, it was found that, because of the rather low efficiency of the optical and detection systems and the alignment problems with the electron beam, this pressure (i.e. molecular density) did not yield enough transitions to make the measurements. The only correction possible short of a major design change was to increase the pressure.

Acceptable measurements for all electron energies (in terms of scaler-timer counts) could be made with the pressure at 10^{-2} torr. A preliminary check of the results at this pressure was made with an accelerating potential of 1000 volts. At this potential and with the pressure at 10^{-4} torr, the current in the beam was sufficient (3×10^{-7} amps) to produce adequate counts to make a good measurement of the cross section. This cross section value was compared with the measurement made at 10^{-2} torr. Since each value fell within the standard deviation of the other, it was concluded that the increase in pressure did not seriously affect the validity of the assumption of negligible collisional de-excitations.

The experiment proceeded as follows: For each electron energy selected, the current in the IAC was peaked and a series of counts at one-hundred-second duration were made for dark and light current. To preclude the possibility of any light from the filament biasing the measurements, the filament voltage was left on during the dark current

counts. Measurements were made at night and on weekends to minimize any possibilities of line voltage fluctuations affecting the measurements.

The temperature in the IAC was not measured directly. However, since all parts of the system had to be operating for several hours in order to stabilize prior to any measurements being taken, the room temperature in the very near proximity to the outer chamber should have very closely approximated the temperature in the interaction chamber.

VI. RESULTS

The effective cross section measurements for the second positive band system of N_2 for bombardment electron energies from 150 eV to 1200 eV are summarized in figure 5. The results vary from 1.4×10^{-17} at 150 eV to 0.2×10^{-17} at 1200 eV, in units of cm^2.

Included in the error estimates are: (1) inaccuracy in reading the temperature, pressure, and electron beam current, (2) the deviation in the calibrated lamp source data (supplied with the lamp) which is included in the statistical standard deviation of the efficiency ϵ, and (3) the statistical standard deviation of the counts C. As noted before the pressure at which these measurements were made may have introduced a small error not accounted for.

The point at 500 eV falls well below the smooth curve of the other points, but it is not believed that this represents a significant difference. There was appreciable unstability in the electronics only at this particular accelerating potential which caused an indeterminate shift.

Measurements of the cross section of the N_2+ first negative band have been made by Srivastava and Mirza /Refs. 5 and 6/, who found that the peak value of the cross section occurred at 100 eV electron energy. Their results are compared with the results of this experiment in figure 6. From this comparison it can probably be assumed that the peak cross section for the second positive band system of N_2 also occurs at 100 eV electron energy.

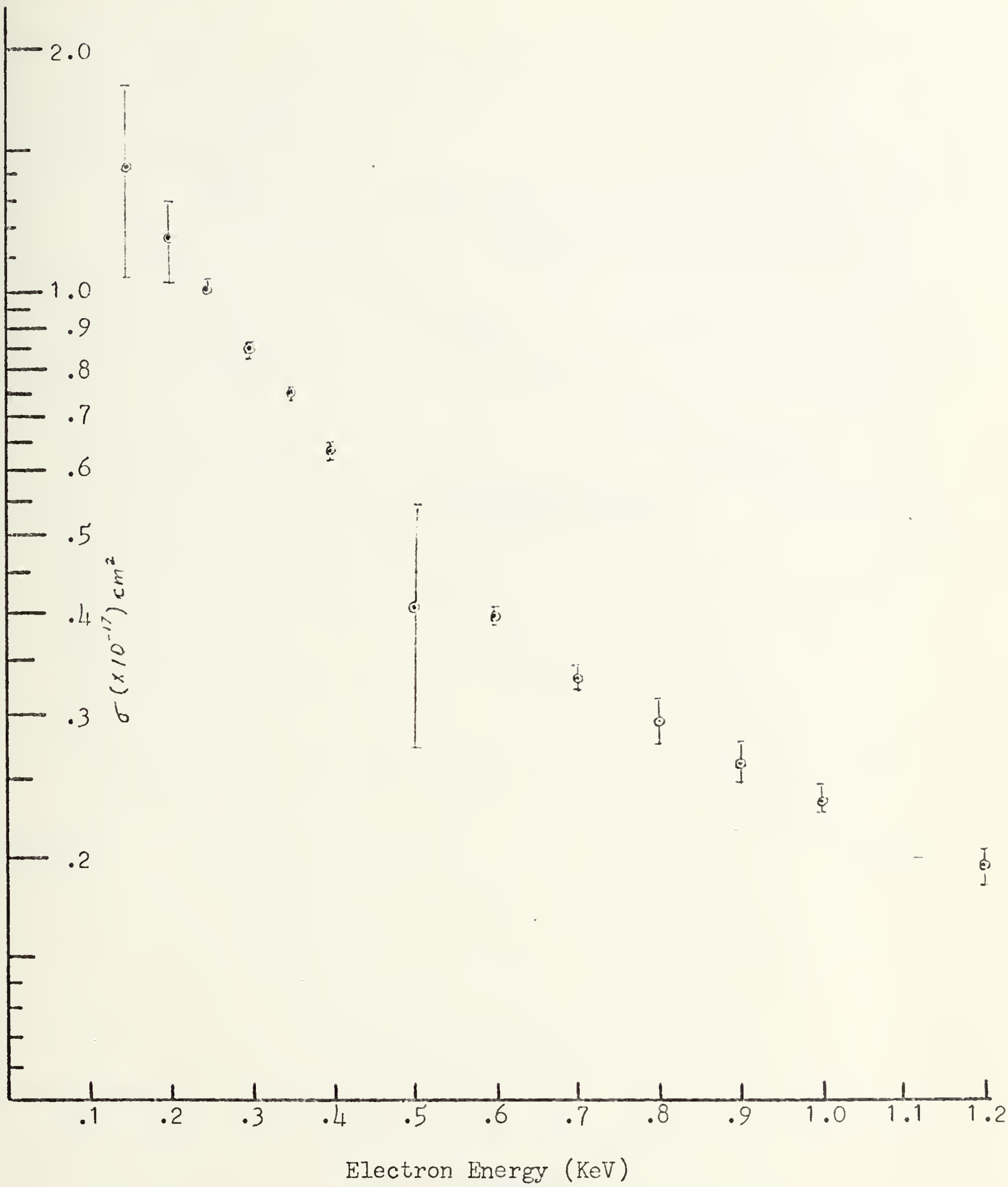

Figure 5. Cross Section vs. Electron Energy

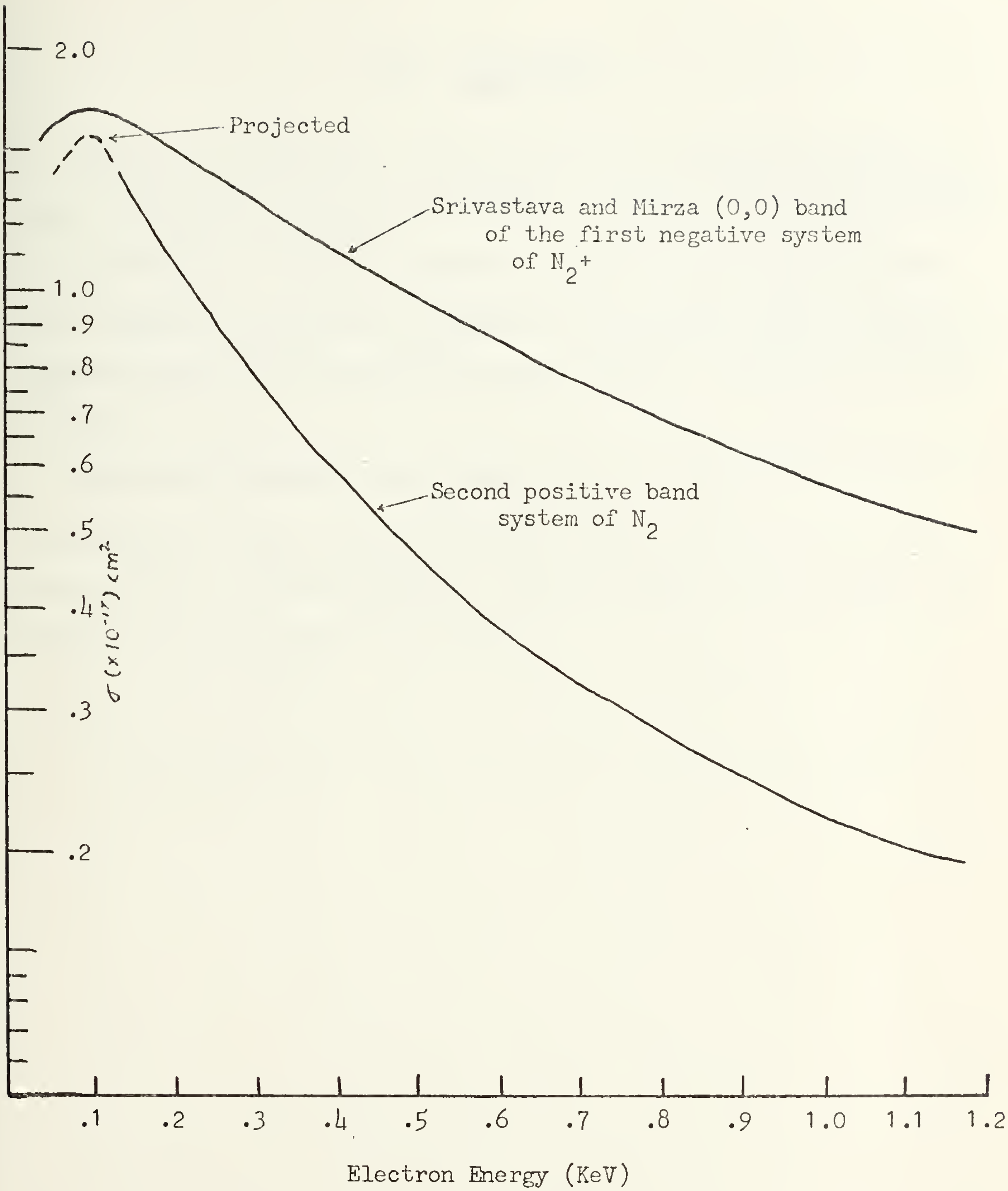

Figure 6. Comparison of Cross Sections

VII. CONCLUSIONS

Because of difficulties cited in this paper, measurements were not made for electron energies below 150 eV. A change of electron gun and/or the design of a device to remotely move the electron gun filament for alignment purposes after the system is closed and under a vacuum, should provide sufficient electron beam current to produce the desired results.

When this problem has been solved and the cross section of the second positive band of N_2 measured for energies below 150 eV, then cross sections of other important atmospheric gases such as oxygen and nitrogen monoxide might be of interest.

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ORIGINATING ACTIVITY (Corporate author) aval Postgraduate School onterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP

REPORT TITLE

he Effective Cross Section for the Production of the $C^3\Pi_u$ State of N_2 when ombarded by Low Energy Electrons

DESCRIPTIVE NOTES (Type of report and, inclusive dates)

aster's Thesis; December 1972

AUTHOR(S) (First name, middle initial, last name)

ames L. Poole, Lieutenant Commander, United States Navy

REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
ecember 1972	29	6

CONTRACT OR GRANT NO. PROJECT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Postgraduate School Monterey, California 93940

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With a gas pressure of about 3×10^{-2} torr, the effective cross section of the second positive system of N_2 under bombardment by 150 eV electrons was found to be $(1.42 \pm .38) \times 10^{-17}$ cm^2. This value is believed to be very near the peak value of the cross section.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6811

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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
CROSS SECTION						
NITROGEN						
SECOND POSITIVE BAND SYSTEM						

Thesis 141406
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c.1 The effective cross section for the production of the $C^3\Pi_u$ state of N_2 when bombarded by low energy electrons.